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MAXIMUM SO2 CONCENTRATIONS PRODUCTED BY A 1000 MEGAWATT POWER PLANT

Enviroplan, Incorporated

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The objective of this study was to predict the largest annual average sulfur dioxide (SO_2) concentrations, maximum 24-hour SO_2 concentrations, and maximum 3-hour SO_2 concentrations produced per year by a new modern 1000 megawatt electric power plant that complies with the federal New Source Performance Standards for SO_2 emissions from coal-fired power plants. The prediction evidence from this study is intended for use in final decisions by the U.S. Environmental Protection Agency concerning federal standards to be promulgated on the subject of nondegradation of air quality. A total of three plant alternatives for complying with new source standards were examined: the use of a scrubber, the use of a scrubber with reheat of emissions, and the use of low sulfur coal.

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MAXIMUM SO_2 CONCENTRATIONS PRODUCED BY A 1000 MEGAWATT POWER PLANT

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Final Report
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CHAPTER ONE: INTRODUCTION AND SUMMARY OF RESULTS

The objective of this study was to predict the largest annual average sulfur dioxide (SO_2) concentrations, maximum 24-hour SO_2 concentrations, and maximum 3-hour SO_2 concentrations produced per year by a new modern 1000 megawatt electric power plant that complies with the federal New Source Performance Standards for SO_2 emissions from coal-fired power plants. The prediction evidence from this study is intended for use in final decisions by the U.S. Environmental Protection Agency concerning federal standards to be promulgated on the subject of nondegradation of air quality.

A total of three plant alternatives were examined:

Case One: Achievement of the New Source Performance Standards for SO_2 through use of a wet limestone SO_2 removal system (scrubber) with conventional reheating of the stack exit gases to 170°F.

Case Two: Achievement of the New Source Performance Standards for SO_2 through use of a wet limestone SO_2 removal system (scrubber) with extreme reheating of the stack exit gases to 250°F.

Case Three: Achievement of the New Source Performance Standards for SO_2 through the use of low-sulfur-content coal.

All three cases were analyzed based on the specified requirement of utilizing a 400-foot stack height in conducting the prediction analyses.

The power plant utilized in all prediction analyses was not an actual existing plant but a plant with operating properties intended to be representative of the operating properties of new modern 1000 megawatt coal-fired power plants that would be build at present. The detailed plant operating data used in this study was developed based on a review of operating properties of several new coal-fired power plants and based on discussions with personnel of the Federal Power Commission, Control Systems Laboratory of the U.S. Environmental Protection Agency, selected electric utility companies several of which have demonstration SO_2 removal system projects, selected stack manufacturers and selected electric utility boiler manufacturers.

The meteorological data used in this study consisted of 8760 separate hourly observations of wind speed, wind direction, stability class and surface temperature for the year 1973 at the Youngstown Airport in Youngstown, Ohio combined with hourly mixing depth values determined from daily surface

and upper-air temperature observations at the upper-air weather station in closest proximity to Youngstown, Ohio--the upper-air weather station in Pittsburgh, Pa. Meteorological data from Youngstown, Ohio was used in this study mainly because climatological summaries of meteorological conditions throughout the U.S. indicated that the meteorological conditions in this area presented a greater than average potential for the buildup of higher air pollution concentrations for extended periods as is typical for much of the Appalachian region of the U.S.

Finally, predictions of SO_2 concentrations were made utilizing Enviroplan's version of the detailed air pollution prediction model developed by the U.S. Environmental Protection Agency and utilized by the U.S.E.P.A. for prediction of the annual average and maximum 24-hour SO_2 concentrations produced per year by principal coal-fired power plants within the U.S. Enviroplan's version of this prediction model included the following additional facilities relevant to this study: 1) Modification of the plume rise formula to account for the differing densities of the stack exit gases as a result of the increased water vapor in the stack exit gases for Case One and Case Two. 2) Use of a more detailed procedure (Enviroplan's MAXSEARCH computer program) for selection of the locations at which to carry out SO_2 predictions. 3) Prediction of the maximum 3-hour SO_2 concentrations produced per year.

Prior to the application of this prediction model, the expected and observed properties of the plumes from coal-fired power plants with and without wet limestone SO_2 removal systems were reviewed to confirm the appropriateness of the gaseous plume diffusion equation employed and to confirm the appropriateness of the Briggs plume rise formula utilized.

Predictions of hourly SO_2 concentrations were made at each of 720 preselected locations surrounding the 1000 megawatt power plant. These 720 locations were specifically selected using Enviroplan's MAXSEARCH computer program to determine the expected locations of the maximum SO_2 concentrations produced by the power plant. For each of these locations,

predictions of hourly SO_2 concentrations were made for each hour of a full 8760-hour year from which the annual average SO_2 concentration at each location was calculated. These results were then organized into separate 24-hour average SO_2 concentrations and separate 3-hour average SO_2 concentrations from which the maximum 24-hour and maximum 3-hour SO_2 concentrations per year were calculated. In summary, for each of the three plant cases examined, a total of 8760 x 720 = 6,307,200 separate hourly SO_2 concentration predictions were made.

A summary of the main results of this study is presented in Table 1-1. These results indicate that the maximum SO_2 concentrations will occur under Case One for which the largest annual average SO_2 concentration, maximum 24-hour SO_2 concentration and maximum 3-hour SO_2 concentration are 1.7 micrograms per cubic meter (ug/m^3), 55 ug/m^3 and 234 ug/m^3 respectively.

The above prediction results are dependent, of course, on the power plant size utilized, the meteorological conditions utilized and the stack heights utilized.

Concerning the dependency of prediction results on power plant size, there are two counterbalancing factors that influence predicted concentrations as power plant size increases beyond 1000 megawatts.

TABLE 1-1: SUMMARY OF RESULTS

	Case One (scrubber, 170°F exit temperature)	Case Two (scrubber, 250°F exit temperature)	Case Three (low-sulfur coal 300°F exit temperature)
Largest annual average SO_2 concentration	1.69	0.98	0.95
Maximum 24-hour SO_2 concentration per year	55.01	40.69	38.44
Maximum 3-hour SO_2 concentration per year	234.28	184.32	173.90

Note: All concentrations are in micrograms per cubic meter (ug/m^3).

On one hand, predicted SO_2 concentrations will increase as power plant size increases due to the increased SO_2 emissions. If other plant properties are held constant, the basic air pollution prediction equations indicate that predicted SO_2 concentrations will increase in direct proportion to increased SO_2 emissions and, hence, in direct proportion to increased power plant size.

On the other hand, however, predicted SO_2 concentrations will decrease as power plant size increases due to the increased heat emissions through the plant stack and the resultant increased plume rise. An increased plume rise serves to lower the maximum ground-level SO_2 concentration produced at any location. The relative importance of increased SO_2 emissions versus increased plume rise as plant size increases varies in a complex way depending on the meteorological conditions and on the downwind distance at which predictions are being made. Nevertheless, it is possible to conclude that as plant size increases, the increase in the resulting SO_2 concentrations will be less than the increase obtained if SO_2 concentrations were assumed to be directly proportional to SO_2 emissions, e.g. for Case One, the maximum 24-hour SO_2 concentration produced by a 2000 megawatt power plant with a single stack will be somewhat less than 2×55 ug/m^3 = 110 ug/m^3 for a plant located in the general vicinity of Youngstown, Ohio in the year 1973.

Concerning the dependency of prediction results on meteorological conditions, this will, of course, vary depending on the local meteorological conditions. For a power plant with a 400-foot stack above the surrounding terrain, the maximum short-term SO_2 concentrations will normally be produced when a period of maximum wind direction persistence (maximum number of consecutive hours in which the wind direction is virtually unchanged) occurs in combination with unstable atmospheric conditions and possibly a limited mixing depth. This combination of meteorological conditions does not normally occur. However, the maximum 3-hour and maximum 24-hour SO_2 concentrations produced by a 1000 megawatt power plant can vary appreciably depending on the degree to which this above condition occurs in any area. Similarly, the largest annual average SO_2 concentrations will also vary depending on the number of hours per year of any designated wind direction. Therefore, it is certain that for a substantial percentage of years in the future (and past), meteorological conditions in the Youngstown, Ohio area will be more adverse and will lead to higher SO_2 concentrations than the meteorological conditions that happened to occur at Youngstown, Ohio in the year 1973--a year selected at random for air pollution prediction purposes. Similarly, for many other areas of the country, meteorological conditions will be more adverse than the 1973 meteorological conditions in Youngstown even though the selection of Youngstown was in part based on the criterion of choosing a

region with greater than average meteorological potential for elevated air pollution concentrations.

Notwithstanding the above qualifications, the prediction results in this study provide an initial best estimate of the maximum SO_2 concentrations produced by a 1000 megawatt power plant.

Furthermore, the results of the MAXSEARCH procedure are helpful in assessing the absolute extreme upper bound on the maximum 3-hour SO_2 concentration produced per year by a 1000 megawatt power plant. In particular, page C-2 of Appendix C indicates that the maximum short-term SO_2 concentration will be produced when stability class A occurs in combination with a wind speed of between 2 and 3 meters per second. This maximum short-term concentration for Case One is 635 ug/m^3 at a downwind distance of 955 meters from the plant. If the mean ten-minute wind direction remains exactly the same for a total of three consecutive hours under the above meteorological conditions, then the maximum 3-hour SO_2 concentration from this plant would be 635 ug/m^3. For this type plant, the above meteorological conditions are highly representative of the critical conditions producing the maximum short-term concentrations. Furthermore, the occurrence of the above described meteorological conditions would be extremely

improbable. Finally, although stability class A is frequently used for air pollution prediction purposes, there is no known confirming scientific evidence that vertical dispersion as extreme as that indicated by stability class A ever, in fact, occurs for plumes with effective stack heights (stack height plus plume rise) similar to the effective stack heights in this study and at downwind distances of on the order of 955 meters or more.

Consequently, the above evidence indicates that 635 ug/m^3 is almost certainly the upper bound on the maximum 3-hour SO_2 concentrations produced by the 1000 megawatt power plants examined in this study regardless of region of the U.S. and regardless of the year of meteorological data utilized in the analysis.

Finally, it is not possible to determine readily similar extreme upper bounds for maximum 24-hour SO_2 concentrations and largest annual average SO_2 concentrations since these depend on the degree of wind direction persistence and on the number of hours per year of the various prevailing wind directions--properties about which it is much more difficult to make meaningful extreme worst-case assumptions.

Next, concerning the dependency of prediction results on stack height, the largest annual average SO_2 concentrations from a 1000 megawatt power plant will decrease significantly

as stack height increases. The maximum 24-hour and maximum 3-hour SO_2 concentrations will also decrease as stack height increases but to a lesser extent than annual average concentrations.

The results of this study are useful in quantifying the benefits versus the costs of extreme reheating of stack gases beyond the conventional average 170°F exit temperature presently used in existing demonstration projects for SO_2 removal systems. An increase in exit temperature from 170°F to 250°F will produce the benefit of a 42 percent reduction in the largest annual average concentration, a 26 percent reduction in the maximum 24-hour SO_2 concentration and a 21 percent reduction in the maximum 3-hour SO_2 concentration. As Chapter Seven indicates, the total cost of achieving this reduction may be on the order of $7,536,000. in capital costs and $1,240,764. in annual operating costs. These incremental capital costs and operating costs are largely independent of moderate changes in the base temperature of 170°F. However, these incremental capital and operating costs will vary approximately in direct proportion to the temperature increment of 250°F - 170°F = 80°F used in the economic analysis in Chapter Seven.

Finally, it is useful to compare the prediction results of this study with the predictions of maximum SO_2

concentrations from studies conducted by contractors to the U.S.E.P.A. as analyzed by U.S.E.P.A. personnel.(1)

The overall conclusions of the above studies were that a 1000 megawatt power plant meeting the New Source Performance Standards for SO_2 with an approximately 400-foot stack above surrounding terrain will in most cases not exceed a maximum 24-hour SO_2 concentration of 100 ug/m^3 and will not exceed a maximum 3-hour SO_2 concentration of 750 ug/m^3. These conclusions were based in part on the application of a limited mixing (trapping) diffusion equation.(2) These conclusions, however, were based largely on a group of previous U.S.E.P.A. detailed prediction studies of existing power plants throughout the U.S.

The prediction results in the above U.S.E.P.A. studies for maximum 3-hour SO_2 concentrations (750 ug/m^3) are fundamentally the same as the 635 ug/m^3 upper bound obtained in this study. However, the maximum predicted 24-hour SO_2 concentrations of 55 ug/m^3 in this study are substantially less than the 100 ug/m^3 obtained in the above U.S.E.P.A. studies for three reasons: 1) The plant examined in this study was a new modern coal-fired plant with a <u>single stack</u> and associated large stack diameter (about 25 feet). The plants examined in the above U.S.E.P.A. studies are existing plants which almost all have one or more stacks with much smaller diameters. Plume

rise increases with increasing stack diameter because of the greater contained volume of hot exit gases with such a stack. Greater plume rise leads to lower ground-level SO_2 concentrations. Thus, the new modern 1000 megawatt power plants with their highly representative single stack designs will produce lower ground-level SO_2 concentrations than existing plants with smaller stack diameters. The results of this study indicate that this conclusion is true even if an SO_2 removal system with reduced stack gas exit temperature is in operation. 2) The above U.S.E.P.A. studies were for several different regions with different meteorological conditions. It is likely that one or more of these regions had more adverse meteorological conditions than the conditions occurring in Youngstown, Ohio in 1973. 3) Some of the power plants in the above U.S.E.P.A. studies had stacks with stack heights as small as 300-feet. This compares with the 400-foot stack employed in this study.

Reference Footnotes to Chapter One

(1) Memorandum from Model Application Section of Source Receptor Analysis Branch, Monitoring and Data Analysis Division, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, "Nondegradation and Power Plant Size," Research Triangle Park, N.C., 1974.

(2) U.S. Environmental Protection Agency, "Requirements for Preparation, Adoption, and Submittal of Implementation Plans," Appendix A, Federal Register, August 14, 1971, CFR 36:15494.

CHAPTER TWO: THE DATA USED IN THE PREDICTION OF AIR POLLUTION CONCENTRATIONS

Two main sets of data are utilized in the prediction of air pollution concentrations in this study: 1) power plant operating data, and 2) meteorological data. These two sets of data are described respectively in Sections 2.1 and 2.2. Finally, Section 2.3 discusses the degree to which the meteorological conditions and resulting predicted SO_2 concentrations in this study are representative of the meteorological conditions and predicted concentrations that would result in other parts of the U.S.

2.1 The Power Plant Operating Data Used in This Study

The following main power plant operating data is required in the prediction of SO_2 concentrations:

a) stack height,

b) stack gas exit velocity,

c) stack gas exit temperature,

d) inside stack diameter at stack top,

e) ratio of the density of the exit gases at the stack top to the density of ambient air at the same temperature,

f) SO_2 emission rate.

Table 2-1 presents a summary of the plant operating data used to predict SO_2 concentrations for the three plant cases under study. The following six subsections discuss the basis for the results summarized in Table 2-1.

TABLE 2-1: SUMMARY OF THE PLANT OPERATING DATA USED IN THE THREE PLANT CASES FOR WHICH SO_2 PREDICTIONS WERE MADE

	Case One	Case Two	Case Three
Effective plant size (megawatts)	1000	1000	1000
Stack height (feet)	400	400	400
Stack diameter (feet)	24.4	26.3	24.5
Gas exit velocity (feet/second)	100	100	100
Gas exit temperature	170°F	250°F	300°F
Ratio of density of exit gases to density of ambient air at same temperature	0.9929	0.9929	1.0180
SO_2 emission rate (tons/hour)	5.610	5.786	5.400

2.1.1 Stack Height

A specified requirement of all analyses was to utilize a stack height of 400 feet above the surrounding terrain.(1) The selection of this stack height is intended to be consistent with the U.S. E.P.A.'s developing definition of a stack that represents "good engineering practice".

2.1.2 Stack Gas Exit Velocity

In the design of a new power plant, stack gas exit velocity is established at a value consistent with good engineering practice, i.e. at a value such that downwash of plume from the stack will not occur under the highest conceivable wind speed conditions at stack top. Based on discussions with stack manufacturers(2) and based on a review of the design stack gas exit velocities for several planned new coal-fired power generation units, the value of 100 feet per second exit velocity was selected as a representative exit velocity.

At exit velocities substantially in excess of this, the plume rise is adversely affected due to the increased turbulence of the rising plume and the associated reduction in the buoyancy component of plume rise. At exit velocities substantially less than this, the potential for downwash from the stack increases under high-wind conditions.

2.1.3 Stack Gas Exit Temperature

For Cases One and Two, the stack gas exit temperature is determined by the sum of the flue gas temperature at the exit point from the scrubber in the SO_2 removal system plus the temperature increment introduced through the reheating of the flue gases prior to emission from the stack.

For existing power plant demonstration projects for SO_2 removal systems, the range of flue gas temperatures at the exit point from the scrubber (scrubber outlet) is consistently between 120°F and 130°F with an average of about 125°F.[3],[4] The only known exception to this is one plant with a scrubber outlet temperature of 100°F. Thus, a scrubber outlet temperature of 125°F is used in this study.

In addition, for existing power plant demonstration projects, the temperature increments actually used or possible through reheating of the exit gases range from 25°F to about 75°F with an average temperature increment of between about 40°F and 50°F.[3],[5] Besides these existing demonstration projects, there is a 10 megawatt experimental project at one electric utility company where up to a 125°F temperature increment can be introduced through reheating.[3]

Based on the above evidence, an average reheating temperature increment of 45°F is used for Case One in this study--the plant case representing a conventional degree of exit

gas reheating. In addition, a reheating temperature increment of 125°F is used for Case Two in this study--the plant case representing extreme reheating of the exit gases.

Therefore, the overall stack gas exit temperature used in Case One is 125°F + 45°F = 170°F. The overall stack gas exit temperature used in Case Two is 125°F + 125°F = 250°F.

Finally, a stack gas exit temperature of 300°F is used in this study for Case Three--the plant case involving the use of low-sulfur coal without an SO_2 removal system. This exit temperature is representative of the design exit temperatures for new coal-fired electric power plants.

2.1.4 Inside Stack Diameter at Stack Top

Once the stack gas exit velocity, stack gas exit temperature and other power plant operating data is determined, the inside stack diameter is entirely specified as a result of the above operating restrictions.

In addition to exit velocity and exit temperature, there are four other main power plant operating properties that determine the stack diameter: a) heat rate of the power plant, b) heat content of the coal used, c) percent excess air used in the combustion process, and d) the mass of water vapor in the stack exit gases.

The power plant heat rate is the number of BTU's of input fuel energy required to produce one kilowatt-hour (KWH) of output electric energy. Table 2-2 presents a summary of the heat rates employed in the three cases under study.

Starting with Case Three, a heat rate of 9000 BTU's per KWH is utilized for a new modern coal-fired power plant burning low-sulfur coal without an SO_2 removal system. This heat rate is based on the estimated average heat rate for the new coal-fired power plants presently beginning operation.(6),(7) Furthermore, the evidence from which this heat rate was determined discloses no systematic relationship between plant size and heat rate.

Determination of the heat rate under Case One requires a determination of the additional BTU's per KWH required for operation of the SO_2 removal system prior to consideration of reheating plus a determination of the additional BTU's per KWH required to reheat the exit gases by $45^{o}F$.

The energy cost of operating a wet limestone SO_2 removal system before consideration of reheating consists mainly of the electric energy costs for the fans, pumps and miscellaneous equipment in the SO_2 removal system. This cost will vary by power plant. Based on discussions with selected electric utilities having demonstration SO_2 removal system

TABLE 2-2: HEAT RATES FOR THE THREE CASES UNDER STUDY

	Case One	Case Two	Case Three
Original plant heat rate (BTU's/KWH)	9000	9000	9000
Additional BTU's/KWH for electric energy requirements of SO_2 removal system	184	184	
Additional BTU's/KWH for reheat of exit gases	166	460	
Total Heat Rate	9350	9644	9000

projects, based on the results of studies by the U.S. E.P.A., and based on recently published data in a trade publication, this overall energy cost for existing retrofitted demonstration projects ranges between about 2% and 3% of the rated capacity of the power plant. For a newly designed modern power plant that includes the SO_2 removal system in the original design, it seems reasonable to assume that some improvement in efficiency will be achieved. Because of this, an energy cost for the SO_2 removal system (exclusive of reheat costs) of 2% of rated capacity is used for the new modern coal-fired power plant analyzed in this study. This energy cost translates into an increase in the heat rate of the power plant by 184 BTU's per KWH.

The energy cost of reheating flue gases by 45°F prior to exit from the stack will vary depending on the method of reheating employed. The five basic methods of reheating exit gases are described in Chapter Seven. Of these methods, steam injection through a direct steam coil heat exchanger downstream of the scrubber outlet is reasonably widely in use and is reasonably representative of the energy costs that are involved with reheating.(3) Based on the use of this method of reheating and based on an examination by the U.S. E.P.A. of several existing demonstration projects, an energy cost of on the order of 2% of the plant rated capacity was estimated to

achieve a reheat temperature increment of 50°F.[3] This translates into an energy cost of about 184 BTU's per KWH. Since the specific heat of air is approximately constant over the range of possible exit gas temperatures within the stack, it follows that approximately (45/50)(184) = 166 BTU's/KWH is the approximate additional energy cost of achieving a reheat temperature increment of 45°F.

Therefore, in Case One, the total heat rate is 9000 + 184 + 166 = 9350 BTU's/KWH.

Finally, Case Two is identical to Case One except that the reheat temperature increment is 125°F. Using the same analysis as above, it follows that the energy cost of reheating exit gases by 125°F is about (125/50)(184) = 460 BTU's/KWH. Thus, the total heat rate in Case Two is 9000 + 184 + 460 = 9644 BTU's/KWH.

The second additional plant operating property that determines the stack diameter is the heat content of the coal burned. The average heat content of the coal used by state ranges from a minimum average of about 11,200 BTU's per pound to a maximum average of about 13,540 BTU's per pound with an overall nationwide average of approximately 12,500 BTU's per pound.[8] Since power plants typically burn a coal with a somewhat smaller heat content than major specialized industrial

users such as steel companies, an average coal heat content of 12,000 BTU's per pound is used in this study.

The third additional plant operating property that determines the stack diameter is the percent excess air used in the combustion process. For new modern coal-fired power plants, this percent excess air ranges between about 15% and 28%.[5],[9] A value of 20% excess air is used in this study.

The final additional plant operating property that determines the stack diameter is the mass of water vapor in the stack exit gases. When flue gases leave the scrubber, they are fully saturated with water vapor at the scrubber outlet temperature.[3] For a scrubber outlet temperature of 125°F, this amounts to an amount of water vapor of about 0.0955 pounds per pound of dry air.[10]

Based on the above plant operating properties, the inside stack diameter at stack top is calculated by determining the total pounds of air and total pounds of water vapor in the stack exit gases, by translating this into the total volume of exit gases at the stack gas exit temperature, and by applying the 100 feet per second stack gas exit velocity when the power plant is generating an effective output of 1000 megawatts.

The details of these calculations are presented in Table 2-3. These results ranging from 24.41 to 26.32 feet

TABLE 2-3: EXIT GAS VOLUMES AND STACK DIAMETERS FOR THREE PLANT CASES UNDER STUDY

	Case One	Case Two	Case Three
Exit gas temperature	170°F	250°F	300°F
Heat rate (BTU's/KWH)	9350	9644	9000
Pounds of air used[a] per lb. of coal burned @ 20% excess air	11.8416	11.8416	11.8416
Total lbs. of coal[b] burned per hour	779,167	803,667	750,000
Total lbs. of air used per hour	9.2266×10^6	9.5167×10^6	8.8812×10^6
Total lbs. of water[c] vapor used per hour	0.8811×10^6	0.9088×10^6	
Total volume of air[d] (cubic ft. per second)	40,568	47,156	47,112
Total volume of water vapor (cubic ft. per second)	6,228	7,240	
Total volume of exit gases at exit temperature (cubic ft. per second)	46,800	54,396	47,112
Exit velocity (ft. per second)	100	100	100
Stack diameter[e] (ft.)	24.41	26.32	24.49

Notes to Table 2-3

(a) Source is from Reference (9) of this chapter.

(b) This is based on an effective electric power output of 1000 megawatts and a coal heat constant of 12,000 BTU's/lb.

(c) For Cases One and Two, this is based on exit gases being fully saturated with water vapor at the exit point from the scrubber at an exit temperature of 125°F. Based on this, Reference (10) indicates there are .0955 lbs. of water vapor per lb. of dry air from which the mass of water vapor is calculated.

(d) Per pound of gas, the volumes of dry air, water vapor, and flue gas from coal combustion without an SO_2 removal system are as follows:

Exit Temperature	Volume of 1 lb. Dry Air (cubic feet)	Volume of 1 lb. Water Vapor (cubic feet)	Volume of 1 lb. of Flue Gas (cubic feet)
170°F = 349.7°K	15.8286	25.447	-
250°F = 394.1°K	17.8383	28.678	-
300°F = 421.9°K	-	-	18.759

(e) Stack diameter $= (4/\Pi)^{.5}/((\text{exit velocity})(\text{volume of exit gases}))^{.5}$

diameters are consistent with new modern power plant designs and are consistent with the qualitative judgments expressed on this subject by stack manufacturers.(2)

2.1.5 Ratio of the Density of the Exit Gases at Stack Top to the Density of Ambient Air at the Same Temperature

This ratio is necessary in the calculation of the plume rise from the power plant.

Since the ratio of densities for gases is independent of temperature, it follows that the ratio of densities will be the same in both Case One and Case Two.

For Case One, the density of the stack exit gases can be calculated by dividing the total unit mass by the volume which this mass fills at an exit temperature of 170°F. As discussed in Subsection 2.1.3, the exit gases at the scrubber outlet will be fully saturated with water vapor. At a 125°F outlet temperature, this amounts to about .0955 pounds of water vapor per pound of air or a total unit mass of 1.0955 pounds.

The volume filled by this unit mass at a 170°F stack gas exit temperature is as follows. One pound of dry air (molecular weight of 28.97) fills 15.8286 cubic feet of volume at 170°F. Therefore, in the case of water vapor (molecular weight of 18.02), .0955 pounds of water vapor fill .0955 (28.97/18.02)(15.8286) = 2.4302 cubic feet.

In addition to water vapor, the other component in the exit gases consists of dry flue gas for which the volume filled per pound of dry flue gas is about 15.0340 cubic feet at a 170°F exit gas temperature.(9)

Therefore, the overall density of the exit gases at a 170°F exit temperature is (1.0955)/(2.4302 + 15.0340) = .062728 lbs. per cubic foot. This compares with a density of ambient air at a 170°F exit gas temperature of .063177.

Finally, the ratio of densities of the exit gases to ambient air at the same temperature is (.062728/.063177) = .9929 for Case One and for Case Two.

For Case Three, the ratio of the density of the exit gases to the density of ambient air is typically about 1.0180 over a wide range of sulfur and carbon contents of the coal burned.(9)

2.1.6 SO_2 Emission Rate

The federal New Source Performance Standard for SO_2 emissions from new coal-fired power plants is 1.2 pounds of SO_2 per million BTU's of fuel input. Thus, there will be small differences in SO_2 emission rates among the three cases under study due to the differences in the number of BTU's of input fuel required to produce the same 1000 megawatt hours of effective electric energy output each hour.

This SO_2 emission rate is calculated as follows:

$$\begin{array}{l} SO_2 \text{ Emission} \\ \text{Rate in Tons/Hour} \end{array} = \begin{array}{l} (10^6 \text{ KWH effective}) \\ (\text{output per hour}) \end{array} \begin{array}{l} (\text{Heat Rate}) \\ (\text{in BTU's/}) \\ (\text{KWH}) \end{array} \begin{array}{l} (1.2 \text{ lbs. } SO_2) \\ (\text{per } 10^6 \text{ BTU's}) \\ (\text{fuel input}) \end{array}$$

2.2 The Meteorological Data Used in This Study

Five sets of meteorological data are required in the prediction of SO_2 concentrations.

1. wind direction
2. wind speed
3. stability class
4. ambient temperature
5. mixing depth

To assure the most accurate prediction of annual average, maximum 24-hour, and maximum 3-hour SO_2 concentrations, this data should be available as separate consecutive meteorological observations once every ten minutes throughout an entire year, i.e. 52,560 separate consecutive observations of the above five meteorological properties. Because meteorological observations at ten-minute intervals are presently not available, all prediction analyses in this study were conducted using 1973 meteorological observations at one-hour intervals throughout the complete 8760-hour year.

This section is divided into two parts. First, the specific meteorological data used in this study is described. Second, a summary of the 1973 meteorological conditions in the

Youngstown, Ohio area is presented.

For wind direction, wind speed, stability class and ambient temperature, the hourly meteorological data from the Youngstown Airport in Youngstown, Ohio was employed. Stability classes from Pasquill classes A to F were utilized. The use of classes E and F were intended to ensure that the meteorological conditions were representative of a relatively large rural region surrounding Youngstown, Ohio.

The mixing depth is the height above ground-level within which the vertical mixing of an emitted pollutant is for all practical purposes confined. The mixing depth depends on the turbulent structure of the atmosphere. In addition, the turbulent structure of the atmosphere is closely related to the vertical temperature structure of the atmosphere. Since it is much more difficult to measure atmospheric turbulence than to measure the accompanying vertical temperature gradients, the latter have frequently been used as an index of the former. Hence, the mixing depth can be calculated approximately from the vertical temperature structure of the atmosphere. From a given surface temperature at a given hour and from the corresponding vertical temperature profile at that same hour, the mixing depth for the hour is calculated as the height above ground at which the dry adiabatic extension of the surface temperature (-1°C per 100 meters) intersects the vertical temperature profile. Figure One illustrates this procedure.

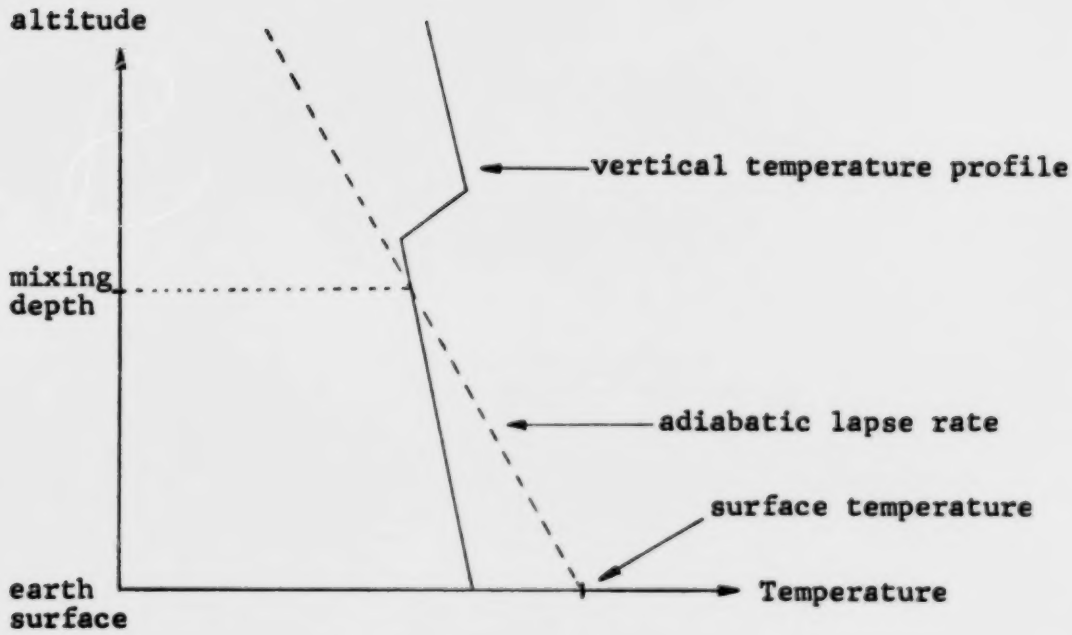

Figure One: Procedures For The Calculation Of Mixing Depths

Since hourly vertical temperature profiles have not been measured anywhere in the general vicinity of the study area, there is a need to utilize procedures which permit an approximation to the hourly mixing depth throughout the full year. At most upper-air weather stations, two soundings (vertical temperature profiles) are taken each day throughout the year. One is taken in the morning and the other in the afternoon. The closest upper-air weather station to Youngstown Ohio is at the Pittsburgh Airport near Pittsburgh, Pennsylvania. In addition, both this station and the Youngstown area are considerably inland from any large water bodies. Hence, the mixing depths determined from the vertical temperature profiles and surface temperatures in the Pittsburgh area should be representative of the actual mixing depths in the Youngstown area. Hourly surface temperatures and the vertical temperature profiles at the Pittsburgh Airport for the full year 1973 were utilized to determine the hourly mixing depths in the Youngstown area throughout 1973.

With two vertical temperature profiles per day, the best way to approximate the hourly mixing depth would be to obtain the hourly profile of vertical temperature constructed from a time interpolation between the two observed vertical profiles. Then the hourly mixing depth would be calculated from the intersection of the adiabatic extension of the hourly surface temperature for each hour and the corresponding profile of vertical temperature for that hour. Such an

algorithm for mixing depth determination is presently under development by the Division of Meteorology of the U.S. Environmental Protection Agency.(11)

Because of the incompleteness of present research in this area, a somewhat more simplified procedure is used in this study to calculate hourly mixing depths. This procedure consists of using the morning vertical temperature profile to represent the vertical temperature structure for the 24-hour period. The hourly surface temperature at the Pittsburgh Airport is used with the above vertical temperature profile to determine an hourly mixing depth for each hour of the day. If there exists no intersection of the adiabatic extension of the surface temperature and the vertical temperature profile, the mixing depth itself is undefined and for air pollution prediction purposes is set equal to infinity.

The use of the above procedure is most appropriate for determining the hourly mixing depths in relatively rural areas similar to the location of the Pittsburgh Airport. In urban areas, a temperature increment would first be added to the surface temperature before calculation of the mixing depth. Thus, the mixing depths utilized in this study are representative of the mixing depths in a relatively large rural region surrounding Youngstown, Ohio and Pittsburgh, Pennsylvania.

In summary, the 1973 meteorological conditions in the vicinity of Youngstown, Ohio were as follows.(13) Prevailing wind directions were from the south (9.2% of time), southwest (10.5% of time), west-southwest (10.0% of time) and west (10.2% of time). The average surface wind speed during 1973 was 8.3 knots or 4.3 meters per second. The frequency of occurrence of each Pasquill stability class was 0.2% for Class A, 3.7% for Class B, 8.5% for Class C, 63.3% for Class D., 11.2% for Class E, and 13.1% for more stable conditions. Mixing depths in this area generally range from typical morning mixing depths of on the order of 500 meters to typical afternoon mixing depths of on the order of 1500 meters.(2) Finally, climatological summaries of the Appalachian region south of Pittsburgh, Pa. indicate wind speed and mixing depth conditions that are highly representative of the wind speed and mixing depths recorded in the Pittsburgh-Youngstown area.(12)

2.3 The Degree to Which the Meteorological Conditions and Resulting Predicted SO_2 Concentrations in This Study are Representative of the Meteorological Conditions and Predicted Concentrations that Would Result in Other Parts of the United States

For a typical 1000 megawatt power plant with a 400-foot stack above the surrounding terrain, the limiting meteorological conditions under which the maximum short-term (24-hour and 3-hour) SO_2 concentrations will be produced are as follows:

a. Wind Direction. Twenty-four hour period and three-hour period of maximum wind direction persistence throughout the year. Maximum short-term concentrations are very heavily dependent on the extent of wind direction persistence.

b. Stability Class. Unstable conditions characterized by Pasquill Class A, B or C. These unstable conditions rapidly bring the power plant plume to ground-level before substantial dilution in the crosswind direction has taken place.

c. Wind Speed. Minimum wind speed (when combined with highly unstable conditions). The horizontal wind speed affects the rate of plume dilution with lower wind speeds producing a slower rate of dilution and higher air pollution concentrations. It should be noted that lower wind speeds also lead to greater plume rises. However, the potential benefits of greater plume rise are largely negated in the presence of highly unstable conditions.

d. Ambient Temperature. Maximum ambient temperature. Increased ambient temperatures reduce the buoyancy and total plume rise. However, the impact of this meteorological condition on maximum concentrations is quite small.

e. Mixing Depth. Minimum mixing depth subject to the qualification that the mixing depth exceed the effective stack

height (plume rise plus stack height) of the source. The mixing depth determines the total volume within which the plume mixes and thus a smaller mixing depth produces a smaller mixing volume and larger SO_2 concentrations. In practice, this meteorological condition is usually of lesser importance than wind direction persistence, stability class and wind speed in determining the maximum concentrations.

Presently available comparative meteorological data from weather stations throughout the U.S. is inadequate for determining how the meteorological data used in this study compares with meteorological data in other areas of the U.S. with respect to the potential for producing maximum SO_2 concentrations.

Nevertheless, there is some useful available data on this subject. First, the three Pasquill Classes A, B and C do, in fact, occur with reasonable frequency in the meteorological data used in this study as described in Section 2.2. Secondly, using mixing depths and wind speeds for a five-year period, Holzworth[14] has ranked 62 weather stations throughout the United States in terms of their potential for the buildup of elevated air pollution concentrations for periods of one to five consecutive days. The weather station in the Holzworth study that was in closest proximity to Youngstown, Ohio is the weather

station at Pittsburgh, Pa. This weather station's ranking ranged from 19th to 26th out of the total of 62 weather stations in this study with a separate ranking being provided for each of the five time intervals treated in this study. The results of Holzworth's study are not entirely relevant to the meteorological conditions under which maximum air pollution concentrations will be produced by an isolated point source of air pollution emissions with a relatively large effective stack height such as a coal-fired electric power plant. Nevertheless, the above rankings do provide useful evidence which indicates that the meteorological data used in this study was data from an area with a greater than average potential for the buildup of elevated air pollution concentrations for extended periods of time.

Finally, although the meteorological data used in this study has a greater than average potential for producing elevated SO_2 concentrations from the 1000 megawatt power plant that was studied, it is important that a case by case analysis be conducted for each actual proposed power plant--a case by case analysis that would utilize the actual meteorological conditions in the vicinity of that proposed power plant. A case by case analysis is important because the combination of critical meteorological conditions that determines maximum SO_2 concentrations can vary substantially from one plant site to another.

Reference Footnotes to Chapter Two

(1) Private Communication, U.S.E.P.A., Division of Economic Analysis, Office of Program Evaluation, 1974.

(2) Private Communications, M.W. Kellogg & Company and Custodis Company, 1974.

(3) Private Communication, Control Systems Laboratory of U.S.E.P.A. and contractor to Control Systems Laboratory who is completing study of the operational performance of the main SO_2 removal systems in operation at electric power plants.

(4) Thomas C. Elliott, "SO_2 Removal from Stack Gases," Power Magazine, Special Report, September, 1974.

(5) Private Communications, selected electric utility companies, including Kansas City Power & Light Co., Commonwealth Edison Co., Louisville Gas & Electric Co., Ohio Edison Co., and Detroit Edison Co.

(6) Private Communication, Mr. Robert Jimeson, Federal Power Commission, 1974.

(7) Federal Power Commission, 1970 National Power Survey, Volume I, Washington, D.C., 1971, p. I-57.

(8) Private Communications, Department of Interior, U.S. Bureau of Mines, 1974.

(9) Babcock & Wilcox, Steam: Its Generation and Use, New York, N.Y., 1972.

(10) U.S. Department of Health, Education and Welfare, Handbook of Air Pollution, P.H.S. Pub. No. 999-AP-44, U.S. Government Printing Office, pp. 11-14.

Reference Footnotes to Chapter Two (Continued)

(11) Private Communication, G.A. DeMarrais, Division of Meteorology, U.S. E.P.A., 1974.

(12) George Holzworth, Mixing Heights, Wind Speeds and Potential for Urban Air Pollution Throughout the Contiguous United States, U.S. Environmental Protection Agency, AP-101, Research Triangle Park, N.C., January, 1972.

(13) National Climatic Center, Stability Wind Rose for Youngstown, Ohio for 1973, Asheville, N.C., 1974.

(14) George C. Holzworth, Meteorological Episoides of Slowest Dilution in Contiguous United States, PB-229-588, National Technical Information Service, Springfield, Va., February, 1974.

CHAPTER THREE: THE PROCEDURES USED IN THE PREDICTION OF AIR POLLUTION CONCENTRATIONS

The air pollution prediction model used to predict SO_2 concentrations in this study was the Gaussian diffusion model as implemented by the U.S. Environmental Protection Agency for the specific purpose of predicting the annual average and maximum 24-hour SO_2 concentrations produced by large power plants.(1)

Following is a description of this E.P.A. prediction model together with a description of additional facilities that were introduced into this model by Enviroplan to improve the accuracy of predicted SO_2 concentrations in this study.

The basic air pollution diffusion model used consists of the Gaussian plume diffusion equation with the inclusion of multiple plume reflections from the top of the mixing layer and ground-level. The basic Gaussian prediction equation is presented in Reference (2) as equation (3.2). The multiple plume reflections are accounted for by use of an equation basically the same as equation (5.8) of Reference (2). These above equations are employed out to the downwind distance where the vertical dispersion coefficient (6_z) exceeds 1.6 times the mixing depth (L). For receptors located at further downwind distances, prediction equation (3.5) of

Reference (2) is utilized to represent the vertically homogeneous distribution (i.e. complete vertical trapping) of the plume beyond the distance where $6_z = 1.6L$.

In the E.P.A. prediction model and the diffusion model employed in this study, the Briggs plume rise formula[3] is utilized with the downwind distance of maximum plume rise dependent on the heat emissions from the stack. In this formula, the plume rise depends on four stack properties: stack gas exit velocity, stack gas exit temperature, inside stack diameter and density of the stack exit gases.

Prior to the application of this plume rise formula, the detailed properties of the stack exit gases were examined to determine the appropriateness of this plume rise formula in the three cases under study. Case Three is typical of the plant operating conditions for which the Briggs plume rise formula was originally developed. Cases One and Two, on the other hand, involve the prediction of plume rise for exit gases that have a substantially increased quantity of water vapor due to the saturation of the exit gases with water vapor at the scrubber outlet.

In summary, there are three possible outcomes for the water vapor in the exit gases from the power plant:
1) condensation of water vapor may occur in the stack between

the scrubber outlet and stack top, 2) condensation of the water vapor may occur in the plume following exit from the stack but before full plume rise as predicted by the Briggs formula has occurred, and 3) condensation of the water vapor may not occur at all prior to the full plume rise (as predicted by the Briggs formula) being achieved.

An SO_2 removal system for a modern electric power plant by necessity must be designed to prevent condensation of water vapor within the stack. Furthermore, the reheat temperature increases used in Cases One and Two ($45^{o}F$ and $125^{o}F$ respectively) effectively prevent water vapor from reaching its dewpoint temperature within the stack. Thus, condensation of water vapor within the stack will not occur in either Case One or Case Two.

Concerning the possibility of the condensation of the water vapor in the exit gases after exit from the stack but before full plume rise as predicted by Briggs, there are three main processes operating on the exit gases. First, the temperature of the water vapor will decrease after it leaves the stack and will approach its dewpoint temperature at which condensation will occur. On the other hand, there are two processes acting in the opposite direction to prevent water vapor condensation:

a) There is a substantial dilution of the exit gases with ambient air after leaving the stack--a dilution that lowers the temperature at which the water vapor in the plume condenses and, hence, decreases the possibility of condensation.

b) If the water vapor condensation process begins, the heat emitted in the condensation process serves to increase the temperature of the plume--an increase in temperature that may prevent further condensation because of an increase of the plume temperature above its dewpoint.

In addition to the above physical considerations, existing demonstration scrubber projects employing reheat temperatures of about 45°F or larger have not produced reports of condensation of water vapor within the plume prior to full plume rise.(4) Because of the above physical considerations and evidence and because condensation of plume water vapor--even if it occurred--may have an insignificant effect on the plume rise and dispersion of the SO_2 gases in the plume, the plume rise formula used in this study is the direct Briggs formula with the density of the exit gases adjusted to account for the realistic larger quantities of water vapor contained in these gases for Cases One and Two.

To account for the <u>increase in wind speed with height above ground level</u>, the E.P.A. model and the diffusion

model employed in this study use the estimated wind speed at stack top to represent the appropriate wind speed for all plume rise calculations and for all plume diffusion calculations. This estimated wind speed at stack top (U_t) is based on research reported by DeMarrais[5] in an area of level terrain and is calculated as follows:

$$U_t = U_s(H_s/7)^n$$

where U_s is the ground-level surface wind speed as measured at a nearby weather station with measurement instruments situated 7.0 meters about the ground (meters/second),

where H_s is the actual physical height of the stack above ground level (meters), and

where n depends on Pasquill stability class with n = 0.10 for Class A, n = 0.15 for Class B, n = 0.20 for Class C, n = 0.25 for Class D and n = 0.30 for Classes E, F and more stable conditions.

Wind direction at the Youngstown Airport weather station is reported only to the nearest ten degrees and represents the wind direction for about a 60-second averaging time at the beginning of each hour. To represent more accurately the actual wind direction, the E.P.A. model and the diffusion

model employed in this study add a separate randomly-selected number between -5° and +5° to the observed wind direction for each hour of the year. This wind direction is assumed to remain unchanged for the full hour. The use of this assumption of constant wind direction for each full hour serves, clearly, to understate the actual variation in the ten-minute mean wind directions for the six ten-minute periods within each hour. To some extent, this understatement in actual wind direction variation is compensated for by the fact that use of the 60-second mean wind direction at the beginning of each hour to represent the average wind direction for the entire hour will serve to overstate somewhat the actual variation in average hourly wind direction from one hour to the next.

The E.P.A. model employs the Pasquill dispersion coefficients for stability classes A, B, C, D, E and F as published in Turner.[2] These dispersion coefficients, suitable for use with ten-minute mean wind directions, were used in all air pollution predictions in this study.

To determine the location of receptors at which to predict the expected maximum SO_2 concentrations, Enviroplan utilized the following detailed procedure to locate receptors. First, Enviroplan's MAXSEARCH computer program was employed to predict the largest SO_2 concentration produced at each downwind distance based on consideration of thirty-six representa-

tive wind speed/stability class conditions. Results of MAXSEARCH are presented in Appendix A. These largest SO_2 concentrations were predicted at successive 100-meter downwind distances from the plant out to a distance 35 kilometers from the plant and then were predicted at successive 5-meter downwind distances within the 200-meter envelope where the maximum SO_2 concentration occurred in the above MAXSEARCH analysis. Application of MAXSEARCH in this manner in effect permitted the searching of each square kilometer of land surface area in the surrounding region to insure that the location of the maximum SO_2 concentrations produced by the 1000 megawatt power plant had been determined as accurately as possible.

To determine additional locations where largest annual average SO_2 concentrations may occur, the MAXSEARCH computer program was applied a second time utilizing representative average meteorological conditions consisting of stability class D and the median wind speed for this stability class.

Based on the results of the MAXSEARCH computer program, a total of 720 receptors were selected as the main locations at which to predict SO_2 concentrations in this study. These receptors were situated at ten-degree intervals in each of 36 directions about the power plant.

After SO_2 concentrations are predicted at each receptor location described above for each consecutive hour of

a full 8760-hour year, the resulting predictions are organized into annual average SO_2 concentrations, 8737 separate 24-hour moving average SO_2 concentrations and 8758 separate 3-hour moving average SO_2 concentrations from which the maximum 24-hour and maximum 3-hour SO_2 concentrations throughout the year are determined.

Reference Footnotes to Chapter Three

(1) Private Communication, U.S. Environmental Protection Agency, Division of Meteorology, 1973 and 1974.

(2) D. Bruce Turner, U.S. E.P.A., Workbook of Atmospheric Dispersion Estimates, No. AP-26, Research Triangle Park, N.C., 1970.

(3) G.A. Briggs, Plume Rise, U.S. Atomic Energy Commission, Division of Technical Information, November, 1969.

(4) Private Communication, U.S. E.P.A. Control Systems Laboratory and PEDCO Environmental Specialists, 1974.

(5) G.A. DeMarrais, "Wind Speed Profiles at Brookhaven National Laboratory," Journal of Applied Meteorology, Vol. 16, 1959, pp. 181-189.

CHAPTER FOUR: THE LARGEST ANNUAL AVERAGE SULFUR DIOXIDE CONCENTRATIONS PRODUCED BY THREE ALTERNATIVE 1000 MEGAWATT POWER PLANTS

The largest annual average SO_2 concentrations producted by the three alternative 1000 megawatt power plants examined in this study are 1.69 ug/m^3 for Case One, 0.98 ug/m^3 for Case Two and 0.95 ug/m^3 for Case Three.

Table 4-1 presents a summary of these results by quadrant about the power plant. In addition, Appendix D presents the complete detailed prediction results for Case One and a summary of the largest predicted SO_2 concentrations for Cases Two and Three.

TABLE 4-1: SUMMARY OF THE LARGEST ANNUAL AVERAGE SO_2 CONCENTRATIONS

Case	Quadrant[a]	Receptor No.[b]	R(km)[c]	θ(deg)[d]	Concentration (ug/m^3)
Case One: (scrubber, 170°F exit temperature)	I	108	4.5	50	1.69
	II	196	12	90	0.98
	III	368	4.5	180	0.68
	IV	638	16	310	0.85
Case Two: (scrubber, 250°F exit temperature)	I	138	16	60	0.98
	II	198	16	90	0.58
	III	370	5.5	180	0.38
	IV	640	20	310	0.48
Case Three: (low-sulfur coal, 300°F exit temperature)	I	138	16	60	0.95
	II	198	16	90	0.56
	III	370	5.5	180	0.36
	IV	640	20	310	0.46

Notes to Table 4-1

(a) Each quadrant consists of 180 prediction locations (receptors) distributed as follows:

Quadrant	Angles from due North Within Which Receptors for this Quadrant are Located
I	0^o - 80^o
II	90^o - 170^o
III	180^o - 260^o
IV	270^o - 350^o

(b) This receptor number is the number used in the detailed prediction results in the appropriate appendix.

(c) R is the downwind distance from the power plant at which this receptor is located.

(d) θ is the angle from due north at which this receptor is located.

CHAPTER FIVE: THE MAXIMUM 24-HOUR SULFUR DIOXIDE CONCENTRATIONS PRODUCED PER YEAR BY THREE ALTERNATIVE 1000 MEGAWATT POWER PLANTS

The maximum 24-hour SO_2 concentrations produced by the three alternative 1000 megawatt power plants examined in this study are 55 ug/m^3 for Case One, 41 ug/m^3 for Case Two, and 38 ug/m^3 for Case Three.

Table 5-1 presents a summary of these results by quadrant about the power plant. In addition, Appendix E presents the complete detailed prediction results for Case One and a summary of the largest predicted SO_2 concentrations for Cases Two and Three.

Finally, Table 5-2 presents the detailed meteorological conditions occurring during the 24-hour period of maximum 24-hour SO_2 concentration for the three plant cases under study.

TABLE 5-1: SUMMARY OF THE MAXIMUM 24-HOUR SO_2 CONCENTRATIONS

Case	Quadrant[a]	Receptor[b] No.	R[c] (km)	θ[d] (deg)	Concentration (ug/m^3)	Date & Hour Corresponding to the Final Hour of the 24-Hour Period of Maximum Concentrations
Case One: (scrubber, 170°F exit temperature)	I	126	3.5	60	49.16	July 7, Hour 19
	II	287	4	140	31.89	Aug. 28, Hour 18
	III	441	1	220	55.01	July 19, Hour 13
	IV	569	5	280	30.68	July 22, Hour 15
Case Two: (scrubber, 250°F exit temperature)	I	127	4	60	28.99	July 7, Hour 14
	II	281	1	140	23.04	Aug. 19, Hour 13
	III	441	1	220	40.69	July 19, Hour 13
	IV	639	18	310	18.16	Feb. 2, Hour 8
Case Three: (low-sulfur coal, 300°F exit temperature)	I	127	4	60	27.49	July 7, Hour 14
	II	281	1	140	21.74	Aug. 19, Hour 13
	III	441	1	220	38.44	July 19, Hour 13
	IV	639	18	310	17.74	Feb. 2, Hour 8

Notes to Table 5-1

Notes (a), (b), (c) and (d) are the same as the four corresponding notes in Table 4-1.

TABLE 5-2: THE METEOROLOGICAL CONDITIONS UNDER WHICH THE MAXIMUM 24-HOUR SO_2 CONCENTRATIONS OCCUR

MONTH	DATE	DAY	HOUR	U (KNOTS)	TEMP. (F)	DIR (DEG)	SC	L (M)
JUL	18	WED	1	6	060	73	F	9999.99
			2	6	060	109	F	9999.99
			3	4	059	123	F	9999.99
			4	5	059	124	F	9999.99
			5	5	058	106	F	9999.99
			6	2	058	114	F	9999.99
			7	2	058	111	F	9999.99
			8	5	063	120	C	13.87
			9	4	068	173	C	101.95
			10	4	072	179	B	327.75
			11	4	077	271	B	1811.89
			12	5	078	179	A	1846.80
First hour of maximum 24-hour period →			13	6	081	179	B	1863.05
			14	5	079	36	A	1882.98
			15	7	082	245	B	1897.10
			16	4	082	241	B	1914.12
			17	5	082	240	B	1897.10
			18	4	082	276	C	1882.98
			19	5	081	329	C	1863.05
			20	5	078	16	F	9999.99
			21	9	072	48	E	9999.99
			22	5	068	31	F	9999.99
			23	6	066	52	F	9999.99
			24	5	062	98	F	9999.99
JUL	19	THU	1	2	061	118	F	9999.99
			2	2	059	132	F	9999.99
			3	2	057	147	F	9999.99
			4	2	057	157	F	9999.99
			5	2	057	170	F	9999.99
			6	3	055	194	F	9999.99
			7	2	056	161	F	9999.99
			8	3	065	136	B	27.00
			9	5	072	192	C	57.62
			10	5	076	219	B	231.42
			11	6	078	224	B	1572.20
			12	6	079	271	B	1855.29
Last hour of maximum 24-hour period →			13	4	080	36	A	1882.93
			14	4	082	316	A	1765.70
			15	2	083	283	A	1765.70
			16	6	084	240	B	1738.14
			17	4	084	313	B	1738.14
			18	5	083	301	C	1718.55
			19	5	082	297	C	1882.93
			20	4	079	271	F	9999.99
			21	3	073	251	F	9999.99
			22	4	071	45	F	9999.99
			23	5	068	77	F	9999.99
			24	4	065	86	E	9999.99

Notes to Table 5-2

(a) The following notation is used in this table:

U = surface wind speed in knots
DIR = wind direction in degrees
SC = stability class
L = mixing depth in meters

(b) A mixing depth of L = 9999.99 denotes an hour in which the mixing depth is undefined due to the presence of stability class E or F or due to the absence of an intersection between the vertical temperature profile and the adiabatic extension of the surface temperature.

CHAPTER SIX: THE MAXIMUM 3-HOUR SULFUR DIOXIDE CONCENTRATIONS PRODUCED PER YEAR BY THREE ALTERNATIVE 1000 MEGAWATT POWER PLANTS

The maximum 3-hour SO_2 concentrations produced by the three alternative 1000 megawatt power plants examined in this study are 234 ug/m^3 for Case One, 184 ug/m^3 for Case Two and 174 ug/m^3 for Case Three.

Table 6-1 presents a summary of these results by quadrant about the power plant. In addition, Appendix F presents the complete detailed prediction results for Case One and a summary of the largest predicted SO_2 concentrations for Cases Two and Three.

Finally, Table 6-2 presents the detailed meteorological conditions occurring during the three hours of maximum SO_2 concentration for Case One.

TABLE 6-1: SUMMARY OF THE MAXIMUM 3-HOUR SO_2 CONCENTRATIONS

Case	Quadrant[a]	Receptor No.[b]	R[c] (km)	θ[d] (deg)	Concentration (ug/m^3)	Date & Hour Corresponding to the Final Hour of the 3-Hour Period of Maximum Concentrations
Case One: (scrubber, 170°F exit temperature)	I	1	1	0	234.28	July 18, Hour 13
	II	281	1	140	232.25	Aug. 19, Hour 13
	III	482	1.5	240	231.11	July 31, Hour 14
	IV	685	3	340	181.32	July 2, Hour 12
Case Two: (scrubber, 250°F exit temperature)	I	1	1	0	183.91	July 18, Hour 13
	II	281	1	140	184.32	Aug. 19, Hour 13
	III	441	1	220	174.89	July 18, Hour 14
	IV	701	1	350	138.44	July 18, Hour 12
Case Three: (low-sulfur coal, 300°F exit temperature)	I	1	1	0	173.48	July 18, Hour 13
	II	281	1	140	173.90	Aug. 19, Hour 13
	III	441	1	220	164.89	July 18, Hour 14
	IV	701	1	350	130.64	July 18, Hour 12

Notes to Table 6-1

Notes (a), (b), (c) and (d) are the same as the four corresponding notes in Table 4-1.

TABLE 6-2: THE METEOROLOGICAL CONDITIONS UNDER WHICH THE MAXIMUM 3-HOUR SO_2 CONCENTRATIONS OCCUR

MONTH	DATE	DAY	HOUR	U (KNOTS)	TEMP, (F)	DIR (DEG)	SC	L (M)
JUL	18	WED	1	6	060	73	F	9999,99
			2	6	060	109	F	9999,99
			3	4	059	123	F	9999,99
			4	5	059	124	F	9999,99
			5	5	058	106	F	9999,99
			6	2	058	114	F	9999,99
			7	2	058	111	F	9999,99
			8	5	063	120	C	13,87
			9	4	068	173	C	101,95
			10	4	072	179	B	327,75
			11	4	077	271	B	1811,89
			12	5	078	179	A	1844,80
			13	6	081	179	B	1863,05
			14	5	079	36	A	1880,08
			15	7	082	245	B	1897,10
			16	4	082	241	B	1914,12
			17	5	082	240	B	1897,10
			18	4	082	276	C	1880,08
			19	5	081	329	C	1863,05
			20	5	078	16	F	9999,99
			21	9	072	48	E	9999,99
			22	5	068	31	F	9999,99
			23	6	066	52	F	9999,99
			24	5	062	98	F	9999,99
JUL	19	THU	1	2	061	118	F	9999,99
			2	2	059	132	F	9999,99
			3	2	057	147	F	9999,99
			4	2	057	157	F	9999,99
			5	2	057	170	F	9999,99
			6	3	055	194	F	9999,99
			7	2	056	161	F	9999,99
			8	3	065	136	B	27,00
			9	5	072	192	C	59,62
			10	5	076	219	B	231,42
			11	6	078	224	B	1572,20
			12	6	079	271	B	1855,29
			13	4	080	36	A	1882,93
			14	4	082	316	A	1765,70
			15	2	083	283	A	1765,70
			16	6	084	240	B	1738,14
			17	4	084	313	B	1738,14
			18	5	083	301	C	1710,55
			19	5	082	297	C	1682,93
			20	4	079	271	F	9999,99
			21	3	073	251	F	9999,99
			22	4	071	45	F	9999,99
			23	5	068	77	F	9999,99
			24	4	065	86	E	9999,99

First hour ⟶ 11

Last hour ⟶ 16

Notes to Table 6-2

The notes to Table 5-2 are applicable to this table also.

CHAPTER SEVEN: THE ECONOMIC COST OF REHEATING STACK EXIT GASES FROM 170°F to 250°F

In the design of SO_2 removal systems for coal-fired electric power plants, there is design flexibility in the degree of reheating for stack exit gases. Additional reheating produces the benefit of higher exit temperatures, greater plume rise, and lower ground-level air pollution concentrations. Associated with this benefit is the additional cost of reheating the stack exit gases by various degrees.

The purpose of this chapter is to provide an approximate estimate of the additional costs of reheating exit gases from 170°F (Case One) to 250°F (Case Two). These costs together with the air quality benefits described in Chapter One are intended for use in preliminary evaluations of the overall merit of additional reheating of exit gases beyond the approximately 170°F level required by good engineering practice.

The chapter is divided into two parts. Section 7.1 describes the main alternative forms of stack gas reheating now in use in the case of demonstration projects for SO_2 removal systems. Section 7.2 presents an initial economic analysis of the estimated additional costs of reheating exit gases from 170°F to 250°F using a representative reheat method. It was beyond the scope of this study to conduct an exhaustive engineering and economic study of this subject. The results

presented are intended to provide initial cost estimates subject to more detailed refinement through further possible studies.

7.1 Description of the Main Methods of Reheating Stack Exit Gases

There are five main methods[1] of reheating stack exit gases (flue gases):

1. Direct-fired reheating where natural gas or low-sulfur oil is burned downstream of the scrubber outlet and the exit gases are heated directly as they pass over these burners.

2. Flue-gas bypassing where a portion of the total high-temperature flue gases from the combustion process bypass the scrubber and then are recombined with the flue gases passing through the scrubber at a point downstream of the scrubber outlet.

3. Hot air injection where excess heat from the air preheater is introduced into the flue gases downstream of the scrubber outlet, or alternatively, an isolated steam coil heat exchanger heats ambient air that is then injected into the flue gases downstream of the scrubber outlet.

4. Steam injection where steam from the turbine cycle supplies a steam coil heat exchanger located directly

downstream of the scrubber outlet. Flue gases from the scrubber outlet are heated as they pass over this heat exchanger.

5. Recuperative transfer where a heat exchanger is added to transfer heat from the gas inlet of the scrubber to its outlet.

In the following economic analysis, reheat alternative 4. is utilized because of the large number of demonstration projects that employ this alternative and because this alternative is reasonably representative of the midpoint in the range of possible economic costs for the five reheat alternatives.

7.2 The Economic Cost of Reheating

The total incremental cost of reheating stack exit gases from 170°F to 250°F by use of a direct steam coal heat exchanger consists of an incremental capital cost and an incremental operating cost.

The incremental capital cost consists almost entirely of the additional plant capacity that must be devoted to providing steam for reheating. This is so because the reheating of exit gases from 125°F to 170°F will by itself require an initial capital investment in a heat exchanger and appropriate ducts.

As Table 2-2 indicates, the incremental BTU's per KWH for reheating from 170°F to 250°F is approximately 9644 BTU's/KWH for Case Two − 9350 BTU's/KWH for Case One = 294 BTU's per KWH. This, in turn, means that (9644/9350) (1000) = 1031.4 megawatts (MW) of total power output capacity is required to produce the same effective 1000 MW output as the power plant of Case One--a plant with reheat to an exit gas temperature of 170°F.

To a first approximation, the incremental capital cost of reheating from 170°F to 250°F is the capital cost of the additional power plant capacity of 31.4 MW or 31,400 KW needed to achieve this temperature increment.

The mid-1974 average capital cost per kilowatt of new coal-fired power plants of about 1000 MW in size is about $240. per KW with an estimated inflation cost of about 7 to 7.5% per year.(2) Therefore, in terms of 1974 dollars, the incremental capital cost of reheating stack exit gases from 170°F to 250°F is on the order of ($240./KW)(31,400 KW) = $7,536,000.

The incremental annual operating cost of reheating stack exit gases from 170°F to 250°F consists mainly of the additional fuel costs required to achieve this reheat. As Table 2-2 indicates, an additional input fuel cost of 294 BTU's/KWH is required to achieve the additional reheating.

This translates into an annual fuel cost of $294 \times 10^6 \times 8760 = 2.575 \times 10^{12}$ BTU's per year.

In 1973, the nationwide average electric utility cost per million BTU's of coal was $.419.[3] While 1974 figures are unavailable, an increase in average cost of about 15 percent above 1973 levels appears merited in view of energy economic developments within the past year. Therefore, in terms of 1974 dollars, the incremental annual operating cost of reheating stack exit gases from 170°F to 250°F is on the order of ($.419/MMBTU)(1.15)($2.575 \times 10^6$ MMBTU) = $1,240,764. per year.

Finally, the above incremental capital and operating costs are largely independent of moderate changes in the base temperature of 170°F. However, these incremental capital and operating costs will vary approximately in direct proportion to the temperature increment of 250°F - 170°F = 80°F used in the economic analysis. This is so because the specific heat of the exit gases is approximately constant over the range of possible exit temperatures. Thus, the additional energy required to reheat the exit gases is directly proportional to the reheat temperature increment and, hence, the incremental capital and operating costs are also directly proportional to this temperature increment.

Reference Footnotes to Chapter Seven

(1) Thomas C. Elliott, "SO_2 Removal from Stack Gases," Power Magazine, September, 1974.

(2) Electric Utility Generation Plan Book, Power Magazine, New York, N.Y., Spring 1974.

(3) Edison Electric Institute, Economic and Statistics Department, Analysis of Fuel for Electric Generation by the Electric Utility Industry: 1969-1973, July, 1974.

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Quadrant II	(90° - 170°)	D-20
Quadrant III	(180° - 260°)	D-38
Quadrant IV	(270° - 350°)	D-56
2. Summary of Results for Plant Case Two (scrubber, 250°F exit temperature)		
Quadrant I	(0° - 80°)	D-74
Quadrant II	(90° - 170°)	D-75
Quadrant III	(180° - 260°)	D-76
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Quadrant III	(180° - 260°)	D-80
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Quadrant I	(0° - 80°)	F-2
Quadrant II	(90° - 170°)	F-25
Quadrant III	(180° - 260°)	F-48
Quadrant IV	(270° - 350°)	F-71
2. Summary of Results for Plant Case Two (scrubber, 250°F exit temperature)		
Quadrant I	(0° - 80°)	F-94
Quadrant II	(90° - 170°)	F-95
Quadrant III	(180° - 260°)	F-96
Quadrant IV	(270° - 350°)	F-97
3. Summary of Results for Plant Case Three (low sulfur coal, 300°F exit temperature)		
Quadrant I	(0° - 80°)	F-98
Quadrant II	(90° - 170°)	F-99
Quadrant III	(180° - 260°)	F-100
Quadrant IV	(270° - 350°)	F-101